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OVALIZATION OF TUBES UNDER BENDING AND COMPRESSION

By L. J. Demer and E. S. Kavanaugh
University of Notre Dame

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SUMMARY

An empirical equation has been developed that gives
the approximate amount of ovalization for tubes under
bending loads. Tests were made on tubes in the D/t
range from 6 to 14, the latter D/t ratio being in the
normal landing gear range. Within the range of the ser-
ies of tests conducted, the increase in ovalization due
to a compression load in combination with a bending load
was very small, the bending load being the principal fac-
tor in producing the ovalization. The ovalization is a
rather complex function of the bending moment, D/t
ratio, cantilever length, and distance between opposite
bearing faces.

INTRODUCTION

This investigation was proposed because it has been
found that the cantilever landing struts on large air-
planes fail to telescope properly when they are subjected
to side loads. This "freezing" of the strut seriously
impairs the shock absorption of the landing gear. The
failure of the strut to telescope properly has been at-
tributed to the ovalization of the piston when the side
load is applied, and the aim of this investigation has
been to measure this change in diameter of the strut and
to arrive at a satisfactory equation for calculating the
increase in diameter. As far as the authors have deter-
mined, no previous investigation has been made of the
ovalization produced by this type of loading.

SYMBOLS

M   cantilever bending moment, inch-pounds

D   outside diameter of tube, inches

t   wall thickness of tube, inches

w   ovalization, inches

L   cantilever length of tube, inches

J   distance between opposite bearing faces, inches

DESCRIPTION OF APPARATUS

The apparatus and method of loading the test speci-
men are shown in figures 1, 2, and 3. The support, for
the bearings and loading apparatus, consisted of a beam
made of two 16-inch steel channels bolted together by
means of steel plates on top and bottom. This beam was
supported by four screw jacks mounted on each corner of
the beam. A fixed bearing was welded to one end of the
channels to form one end support for the tube to be tested
and a movable bearing was mounted on the top of the chan-
nels to form the second support. The load was applied at
the end of the tube opposite the fixed bearing. A port-
able hydraulic jack was used to apply the bending load
to the tube, a cradle type yoke being used between the
tube and the base of the jack, as shown in figure 3. A
Bourdon type pressure gage was inserted in the hydraulic
line of the jack and was used to determine the load ap-
plied; the gage was calibrated, and the load read from a
curve of load vs. pressure. A similar cradle was used
to apply a compression load (fig. 3b) on the tube through
the use of another hydraulic jack, similarly calibrated.

Several types of deflection gages were tested before
the final gage was decided upon. Two types are shown in
figures 4 and 5; the latter type, figure 5, is the one
with which the most success has been obtained. Figure 4
shows the parallel-arm type gage which was used for the
tests made on the largest tube (diameter 4.610") and on
the second tube (diameter 4.375"). A complete set of

readings was also taken with the second type, the double-
indicator gage, on the 4.375 inch diameter tube. The
deflections indicated by the two types agreed quite close-
ly, but the second type gage was more easily assembled
and is believed to be more reliable. The double-indicator
gage gave direct readings while the parallel-arm type
gave magnified readings which had to be corrected. The
double-indicator type gage was supported on the tube by
four pointed setscrews, the screws being 90° apart and in
contact with the tube at points where the deflection was
either zero or small negatively. The indicators used for
measuring the deflection were of the Jordan type and were
graduated in ten-thousandths of an inch.

An inside gage consisting of a single Jordan type
indicator, mounted so that it measured the change in the
inside diameter at the 90° azimuth, was used for tubes of
4.251 inch diameter and less. The plane in which the ap-
plied load acts was taken as the 0° azimuth, making the
90° azimuth the plane of the neutral axis of the tube.
The readings obtained with this gage were not very reli-
able, but they did indicate that the maximum ovalization
occurred very near station 0 (plane of the face of the
movable bearing on the side of the applied load) as long
as the ovalization did not exceed the bearing clearance.

DESCRIPTION OF TEST ARTICLES AND

METHODS OF PERFORMING TESTS

The test specimen used was made from an SAE X-4130
tube. The original diameter and wall thickness of the
tube was 4-5/8 inches outside diameter × 3/4 inch wall.
The over-all length of the test specimen was 47 inches.
Tensile specimens tested in the University laboratories
indicated the ultimate tensile strength to be 147,500
lb/in.^{2}, and the yield point to be 117,500 lb/in.^{2}. The
Brinell hardness number was about 347. The bearings for
the two supports were made from an SAE 1020 tube. A
heavy sleeve was fitted over the end of the test specimen
in such a manner as to make the distance from the center-
line of the fixed bearing to the centerline of the applied
load 55-1/16 inches. For details of the test setup, see
figures 1 and 2.

The range of D/t ratios, 6 to 14, that was tested

was obtained by reducing the outside diameter of the test
specimen after the series of tests had been conducted at
one D/t ratio. The inside diameter of the tube was held
constant at 3.125 inches. Tests were conducted with out-
side diameters of 4.610, 4.375, 4.251, 3.929, and 3.650
inches. In each case, the outside was ground concentric
with the inside.

     The outside diameters of the tube were held to a
tolerance of ±0.001. The bearing clearance was held be-
tween 0.0020 and 0.0040 inch over the outside diameter of
the tube. This clearance was designed to stay within the
allowable bearing clearances specified for actual landing
gears.

     The first tests were made to determine the points on
the tube where the increase in diameter of the tube was
the greatest, as it was at this point that the tube would
tend to "freeze" in the bearing if the ovalization became
great enough. The axial location of points at which the
measurements were taken are designated by inch stations,
using the plane of the face of the movable bearing on the
side of the applied load as the zero reference station.
(See fig. 2.) The stations between the reference station
and the applied load are considered positive. Measure-
ments were taken at various stations along the length of
the tube from the fixed bearing to station plus 10 inches.
The measurements at each station were taken around the
circumference of the tube, using the vertical centerline
of the tube as the reference point, zero azimuth. Azimuth
readings were taken at 15° increments.

     Six bearing positions, A, B, C, D, E, and F, as
shown in figure 2, were used during the investigation,
the ratio of tube length to the distance between bearings
varying between 15.3 and 2.4. In this case the length of
tube is considered to be the distance (55-1/16 in.) be-
tween the centerline of the fixed bearing and the applied
load and the distance between bearings to be the distance
between their centerlines. In all other places in this
report the distance between bearings is considered to be
the distance between opposite bearing faces (J). This
criterion was chosen because the distance between opposite
bearing faces is a standard designation in strut design
specifications. The six values of J used in this inves-
tigation were 7.12, 12.75, 17.36, 21.97, 26.58 and 31.19
inches. The bearing position distances for positions B
through F vary by increments that are multiples of the
original diameter of the tube, 4.610 inches.

The gages used for measuring ovalization were alined on the tube by scaling the distance from the zero reference station to the centerline of the leg of the dial gage and placing in the correct azimuth by use of a level bubble and a square. The gage was then fastened to the tube so that it supported itself.

Before beginning a test a comparatively heavy load of about 4000 pounds was applied to the tube in order to check the gage for proper alinement. The number and magnitude of the bending loads applied varied with the bearing position and tube diameter. A low load was first applied and then increased in predetermined steps until the maximum load was reached, the reading of the dials of the gage being recorded as each load was applied. At least two sets of readings were taken at each station as a check.

The tests to determine the effect of a compression load on ovalization were made with and without bending loads, the ovalization gage being alined in the same manner as for the tests involving bending loads only. The compression load was applied at the centerline of the tube (see fig. 3b) for one series of tests with and without a bending load and another series of tests with and without a bending load were made with the compression load being applied eccentrically, 4 inches below the centerline of the tube.

The end deflection of the tube was measured for each test and was used to check the applied bending load. The hydraulic gages used in applying the bending load were checked periodically.

The gages used to measure the ovalization were graduated to one-ten-thousandth of an inch. Repeated tests were made at various stations along the tube and such tests indicated that the accuracy of the measurement was within four-ten-thousandths, and it was not unusual for the repeated points to fall within one-ten-thousandth of the original test.

The gages used to measure the oil pressure in the hydraulic jacks were calibrated to read within 30 pounds of the true load.

The complete data gathered during this investigation may be obtained on loan from the Office of Aeronautical Intelligence of the National Advisory Committee for Aeronautics, Washington, D. C.

RESULTS AND DISCUSSION

Numerous measurements were made to determine the
amount of ovalization as the circumference of the tube
was traversed and figures 7 through 10 show some results
of these tests. Measurements were taken of the ovaliza-
tion of the tube at 15° increments from 0° azimuth to
180° azimuth for the test on the original tube only.
All test results are not included in this report, as the
tests were made to find the azimuth at which maximum
positive ovalization occurred so that later measurements
could be concentrated on this one azimuth. This point
was found to be the 90° azimuth point. After the first
tests, measurements were taken only at 0° and 90° azi-
muths. The 0° azimuth readings were taken only as a
matter of record, as they were not considered as a part
of this particular study.

One interesting feature brought out in figures 9
and 10 is that the axis of symmetry shifts downward as
the bearing face, or zero reference station, is approached.
The curve of the ovalization around the circumference of
the tube closely approaches that of a sine curve.

Tests were conducted to determine the point of maxi-
mum ovalization along the length of the tube. The re-
sults of these tests, as shown in figures 11 and 12,
clearly indicate that this point was at the zero refer-
ence station.

The longitudinal and circumferential tests dis-
cussed above were made with the movable bearing placed
at positions B, C, D, and E, although only the data
from the tests with position C are included herein.

Figures 13, 14, 15, 16, and 19 are typical plots
for one bearing position (position C) of the bending
moment at the various stations against ovalization for
the range of D/t ratios that were tested, while fig-
ures 17 through 22 are typical plots for one D/t ratio
(O.D. = 3.650 in.) for the bending moment at the various
stations against ovalization for the different bearing
positions that were used during the tests. The bending
moment is taken as the product of the load and the dis-
tance from the station of measurement to the centerline
of the applied load, this distance for station zero (0)
and the final equation is the lever arm, L, as shown in

figure 1. As the D/t ratio increases the ovalization
vs. bending moment curves change from straight lines to
smooth curves and finally into a type of curve that has
a sharp knee in it (O.D. = 3.650 in.). The bearing
clearance for the tubes with diameters of 4.610 inches
and 4.251 inches was approximately 0.004 inch. The tube
with a diameter of 4.375 inches had a bearing clearance
of approximately 0.010 inch. This clearance exceeds the
normal landing gear bearing clearance. The 3.929 inch
and 3.650 inch diameter tubes had clearances of 0.003 and
0.0025 inch, respectively.

The second series of figures, 23 through 32, are
typical plots of ovalization against distance from the
bearing face, or zero reference station. Figures 23, 24,
25, 26, and 29 present these data for the range of D/t
ratios that were tested with one bearing position (posi-
tion C). Figures 27 through 32 present these data for
tests with all bearing positions for one D/t ratio
(O.D. = 3.650 in.). These curves were plotted to obtain
the general trend of the ovalization as the bearing face
was approached and to permit the extrapolation of the
curves up to the bearing face. The curves were extended
with the assumption of a pseudo-bearing, one that was
somewhat elastic and not as rigid as actual, on the basis
that the ovalization would continue along the same trend
if the clearance between the tube and the bearing re-
mained constant.

Tests were conducted using compression loads in
combination with bending loads and with compression loads
only; these compression loads were applied eccentrically
as well as in straight compression. No noticeable change
in ovalization occurred when the compression loads were
applied, even though the additional bending moment caused
by the eccentric compression load would seem to indicate
that the ovalization should increase. The maximum com-
pression load used was 11,500 lbs. with a bending load of
6,000 lbs. These tests were made on the two tubes having
the smallest thickness of wall. Inasmuch as it is shown
that compression loads in combination with bending loads
had little or no effect on the ovalization resulting from
the bending load only, further tests with compression
loads were not undertaken.

Some tests were also made on the various tubes with
the bearing sleeve removed. The bearing sleeve referred
to in this case is the bearing in the movable bearing.
The bearing sleeve was removed and the movable bearing

base was raised so that the tube was supported in its
original position. While the tests were not too closely
related, the results showed that the slope of the oval-
ization vs. bending moment curve was definitely higher
without the sleeve in place than with it. This higher
slope can be interpreted to mean that the ovalization of
the tube for a given load will increase as the clearance
between the tube and the bearing sleeve is increased,
although the magnitude of this increase has not been
determined. As this effect was not considered until the
investigation was more than half completed, sufficient
data on the actual bearing clearances were not obtained
and this effect could not be included in the final equa-
tion.

The ovalization was a maximum for a given bending
moment at bearing position A, decreasing as the movable
bearing was moved through positions B, C, and E. At
bearing position D, however, the ovalization approaches
that of position C, the reason for this being attributed
to the change in the ratio of the distance between the
opposite bearing faces and the outside diameter. This
reasoning is based on the assumption that the portion
of the tube between the two bearings reacts as a unit
with the two bearings (the same effect as if the two
bearings were rigidly tied together) until the movable
bearing is placed beyond position C. As the movable
bearing is moved toward position D, the fixed bearing
end of the tube reacts as a restrained beam, but at the
movable bearing the effect changes from a fully restrained
to a partially restrained condition, the movable bearing
tending to rotate somewhat with the tube as the load is
applied, relieving some of the actual load on the tube
at station zero.

The results indicate that the ovalization of a tube
increases rapidly with the ratio of the distance between
opposite bearing faces and the D/t ratio. The ovaliza-
tion is dependent, however, not only on this ratio, but
also on the bending moment and on the cantilever length
of the tube.

DEVELOPMENT OF OVALIZATION FORMULA FOR MAXIMUM

POSITIVE OVALIZATION AT STATION ZERO, 90° AZIMUTH

On log-log curve sheets (figs. 33 through 37) were

plotted the data for Ovalization vs. Bending Moment that
were extrapolated to the zero reference station for the
tubes with different ratios of D/t. The straight line
trend of the points so obtained for any one given bearing
position and D/t indicated the following relationship,
which is merely the equation for the straight line on the
log-log plot:

$$w = \frac{a M^b}{10^4}$$

or

$$\log w = \log a + b \log M - 4.0$$

where

w   maximum positive ovalization at station zero,
        90° azimuth, inches

M   cantilever bending moment, inch-pounds

b   slope of the line on the log-log plot

a   constant for any one curve

and

10^4 conversion from ten-thousandths of an inch to inches

Equations were then written for the curves of w vs.
M for each bearing position and each D/t. The results
indicated that the b terms (or slopes) were substan-
tially constant for the curves for a fixed D/t, but
that the a terms varied both with bearing position and
D/t. It was necessary to make the a term of the general
equation a function of both D/t and a value which de-
pended upon the bearing position. The ratio of J to
D/t was therefore used, where J is the distance in
inches between outside bearing faces.

No direct relationship was found for the variation
of the particular a terms with the ratio of J to D/t,
but a plot of log (- log a) vs. the ratio J to D/t,
as shown in figure 38, indicated a straight line varia-
tion for each bearing position with the curves for the
five different bearing positions intersecting at a common
point. Equations were deduced for each of these curves
using the form:

$$\log(-\log a) = 0.10 + s\frac{J}{D/t}$$

or

$$\log a = -10^{\left(0.10 + s\frac{J}{D/t}\right)}$$

where 0.10 is the Y-axis intercept of the five curves
and s is the variable dependent upon bearing position.

No direct relationship was found between s and the
cantilever length, L, but a plot of log [log (10 s)] vs.
log (log L) resulted in a straight line variation (as
shown in fig. 39) for which the following equation was
written:

$$\log[\log(10\ s)] = -3.465 + 14.1920\ \log(\log L)$$

or

$$\log(10\ s) = 0.000343\ (\log L)^{14.1920}$$

where L is the cantilever length, in inches.

As stated on page 9, the trend of the b terms (or
slope of the log-log plot of w vs. M, figs. 33 through
37) indicated that the slopes were substantially constant
for a given D/t. Averaging the practically constant
values of b for the sets of curves with constant D/t,
values of b were obtained which were plotted against
D/t in figure 41. The following empirical equation was
deduced for the curve obtained:

$$b = \frac{\log(D/t) - 1.143}{3.06 - 5.90\ \log(D/t)} + 0.75$$

It is to be noted here that the agreement of the
curves drawn using these slopes with the log-log w vs.
M data for some of the curves of D/t of 7.00 and 7.55
is not as good as for the data with the other D/t
ratios. The data obtained for these two D/t ratios
were obtained using the parallel arm gage as opposed to
the double indicator gages used in obtaining the remain-
der of the data. In addition, the data for the D/t
of 7.55 were obtained using a sleeve with a very large

clearance, hence the increased slope. It is thought, however, that the curve as shown in figure 41 of b vs. D/t gives within reasonable limits the slopes that would have been obtained had the data for these D/t ratios been taken under the same conditions as for the others.

A summary of the empirical equations deduced is as follows:

$$w = \frac{a M^b}{10^4} \tag{1}$$

$$\log w = \log a + b \log M - 4.0 \tag{2}$$

$$\log w = -10^{\left(0.10 + s \frac{J}{D/t}\right)} + b \log M - 4.0 \tag{3}$$

$$\log (10 s) = 0.000343 (\log L)^{14.1920} \tag{4}$$

$$b = \frac{\log (D/t) - 1.143}{3.060 - 5.90 \log (D/t)} + 0.75 \tag{5}$$

In order to facilitate the determination of s in any particular case, values were calculated using formula (4) giving s for a range of cantilever lengths, L, from 10 to 60 inches. Figure 40 contains the curve plotted from these values and it also shows the experimental points from which the equation was deduced.

For determination of b, equation (5) was solved to give values of b for values of D/t from 5 to 20. The results are plotted in figure 41.

The recommended procedure for determining ovalization when M, D/t, J, and L are known, is to determine s from figure 40, determine b from figure 41, substitute these values along with the other knowns in equation (3), and solve for w.

CONCLUSIONS

1. Tubes of the type commonly used in landing gear struts were shown to ovalize to such an extent under normal operating loads that "freezing" of the strut will result if adequate clearance is not allowed in the bearing, or if means are not introduced to stiffen the tube sufficiently to prevent excessive ovalization.

2. The compression load, acting in straight compression or eccentrically, in combination with a bending load does not affect the ovalization. The eccentricity of the compression load in these tests did not exceed four inches and a greater eccentricity may not act in the same manner, as when the bending effect overrides the straight compression effect.

University of Notre Dame,
  Notre Dame, Ind., January 10, 1944.

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Figure 1.- Simplified sketch of the apparatus and method of testing.

Figure 2.- Apparatus for bending and compression tests.

Figure 3a.— Test apparatus for bending load.

Figure 3b.— Test apparatus for bending
and compression load.

Figure 4.- Parallel-arm type ovalization gage.

Figure 5.- Double-indicator type ovalization gage.

Fig. 6

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Figure 6.- Double-indicator type gage on tube at station 1.5

BEARING POSITION C
Initial Tube Diameter, D, 4.610 IN.

Load

Azimuth

$D_L - D = W$

D_L = Diameter under load

AZIMUTH
90°
75°
60°
45°
30°
15°
0°

OVALIZATION, W, INCH

.0020

.0010

0

-.0010

-.0020

-.0030

Relation between ovalization and bending load
for angular settings between 0 and 90 degrees
at station 0.06.

BENDING LOAD - LBS. x 10²

0   20   40   60   80   100   120   140   160

Figure 7

BEARING POSITION C
Initial Tube Diameter, D, 4.610 IN.

AZIMUTH
90°
75°
60°
45°
30°
15°
0°

OVALIZATION, W, INCH

.0006

.0004

.0002

0

-.0002

-.0004

-.0006

Relation between ovalization
and bending load for angular
setting between 0 and 90
degrees at station 4.

BENDING LOAD - LBS. x 10²

0   20   40   60   80   100   120   140   160

Figure 8

Figure 9

Bearing Postiom C
Initial Tube Diameter, D, 4.610 IN.
STATION 0.06

Variation of ovalization with azimuth for a
constant bending load of 14,333 lbs.

Figure 10

BEARING POSITION C
Initial Tube Diameter, D, 4.610 IN
Station 4

Relation between ovalization and azimuth for
a constant bending load of 14,333 lbs.

BEARING POSITION C
Initial Tube Diameter, D, 4.610 IN.
90° Azimuth

LOAD, LBS

The dotted portions of the
curves are extrapolated.

Variation of ovalization
with the distance from
Station zero.

Figure 11   STATION, INCHES

BEARING POSITION C
Initial Tube Diameter, D, 4.610 IN.
0° Azimuth

LOAD, LBS.

Extrapolated curves from
Station 0 to −4 are shown
as dotted lines.

Relation between ovalization
and distance from Station
zero.

Figure 12   STATION, INCHES

BEARING POSITION C
Initial Tube Diameter, D, 4,610 IN.
90° Azimuth
$\frac{D}{t} = 6.21$

OVALIZATION, W, INCHES

STATION
0.06

2

Relation between ovalization
and bending moment for four
positive stations.

4

6

Figure 13

BENDING MOMENT, IN. LBS. x 10³

BEARING POSITION C
Initial Tube Diameter, D, 4,375 IN.
90° Azimuth
$\frac{D}{t} = 7.00$

OVALIZATION, W, INCHES

STATION
1

2

Relation between ovalization
and bending moment for six
positive stations.

3

4
4.5
5

Figure 14

BENDING MOMENT — IN. LBS x 10³

BEARING POSITION C
Initial Tube Diameter, D, 3.251 IN.
90° Azimuth
$\frac{D}{t} = 7.55$

OVALIZATION, W, INCHES

STATION

2

3

4

4.5

5

BENDING MOMENT - IN. LBS. x 10³

Relation between ovalization and bend-
ing moment for five positive stations.

Figure 15

BEARING POSITION C
Initial Tube Diameter, D, 3.929 IN.
90° Azimuth
$\frac{D}{t} = 9.77$

OVALIZATION, W, INCHES

STATION

1

2

3

4

4.5

5

BENDING MOMENT - IN. LBS. x 10³

Relation between ovalization and
bending moment for six positive
stations.

Figure 16

BEARING POSITION A
Initial Tube Diameter, D, 3.650 IN.
90° Azimuth
$\frac{D}{t} = 13.9$

STATION

OVALIZATION, W, INCHES

BENDING MOMENT, IN. LBS. x 10³

Figure 17

> STATION 0.156
○ STATION 0.5
< STATION 1.0

Relation between ovalization and bending
moment for eight positive stations.

BEARING POSITION B
Initial Tube Diameter, D, 3.650 IN.
90° Azimuth
$\frac{D}{t} = 13.9$

STATION

OVALIZATION, W, INCHES

BENDING MOMENT, IN. LBS. x 10³

Figure 18

> STATION 0.156
○ STATION 0.5
< STATION 1.0

Relation between ovalization and bending
moment for eight positive stations.

BEARING POSITION D
Initial Tube Diameter, D, 3.650 IN.
90° Azimuth
$\frac{D}{t} = 13.9$

Relation between ovalization and bending moment for six positive stations.

Figure 20

BEARING POSITION C
Initial Tube Diameter, D, 3.650 IN.
90° Azimuth
$\frac{D}{t} = 13.9$

Relation between ovalization and bending moment for six positive stations.

Figure 19

Figure 22

Initial BEARING POSITION F
Tube Diameter, D, 3.650 IN.
90° Azimuth
$\frac{D}{t} = 13.9$

Relation between ovalization and bending moment for eight positive stations.

Figure 21

Initial BEARING POSITION E
Tube Diameter, D, 3.650 IN.
90° Azimuth
$\frac{D}{t} = 13.9$

Relation between ovalization and bending moment for six positive stations.

Figure 24

Figure 23

BEARING POSITION C
Initial Tube Diameter, D, 4.251 IN.
90° Azimuth
$\frac{D}{t} = 7.55$

OVALIZATION, W, INCHES

Extrapolated curves

BENDING MOMENT
IN. - LBS.

250,000

200,000

150,000

100,000

Variation of ovalization with
distance from bearing face (Station zero)

Figure 25   DISTANCE FROM BEARING FACE, INCHES

BEARING POSITION C
Initial Tube Diameter, D, 3.929 IN.
90° Azimuth
$\frac{D}{t} = 9.77$

OVALIZATION, W, INCHES

Extrapolated

BENDING MOMENT
IN. - LBS.

240000

200000

150000

100000

60000

Variation of ovalization with
distance from bearing face.

Figure 26   DISTANCE FROM BEARING FACE - IN.

BEARING POSITION A
Initial Tube Diameter, D, 3.650 IN.
90° Azimuth
$\frac{D}{t} = 13.9$

BENDING MOMENT IN.-LBS.

180000

160000

120000

80000

40000

Dotted portion of curves are extrapolated.

OVALIZATION, W, INCHES

Variation of ovalization with distance from bearing face.

Figure 27   DISTANCE FROM BEARING FACE - IN.

BEARING POSITION B
Initial Tube Diameter, D, 3.650 IN.
90° Azimuth
$\frac{D}{t} = 13.9$

BENDING MOMENT - IN. LBS.

200,000

160,000

120,000

80,000

60,000

40,000

The dotted portions of the curves are extrapolated.

OVALIZATION, W, INCHES

Variation of ovalization with distance from the bearing face (Station zero)

Figure 28   DISTANCE FROM BEARING FACE, INCHES

BEARING POSITION C
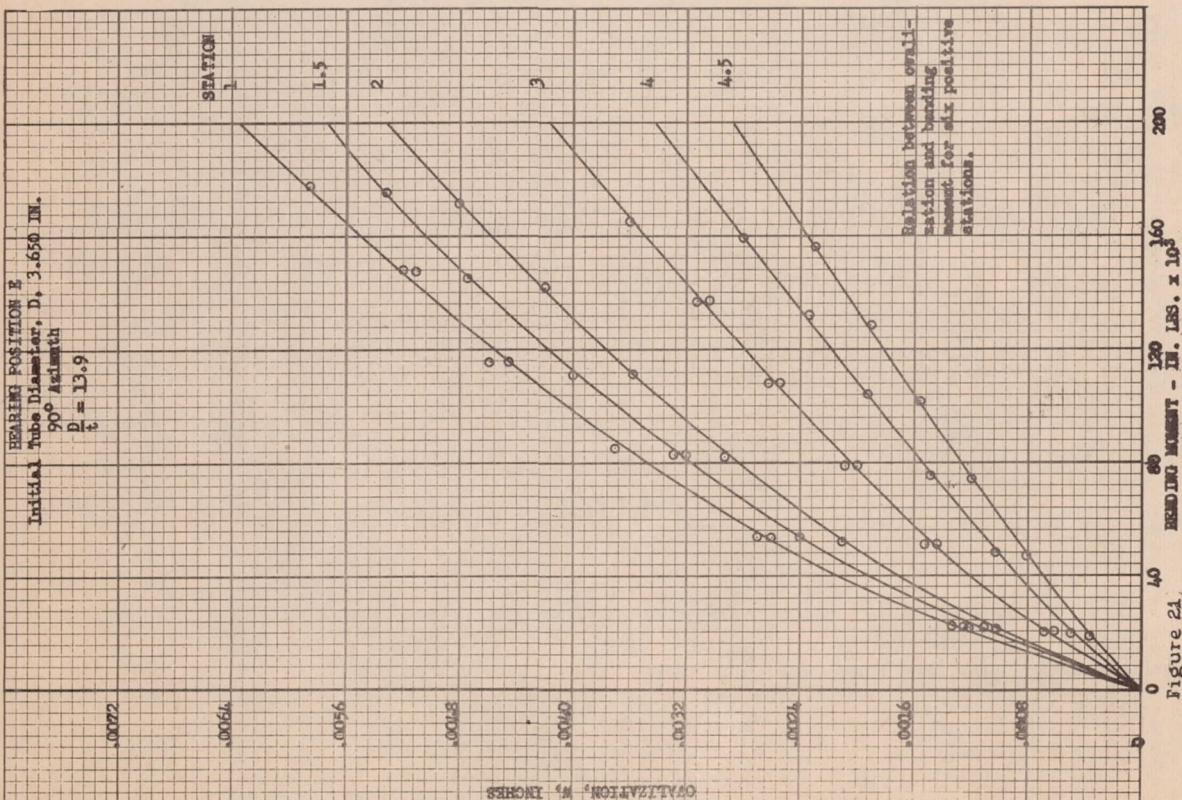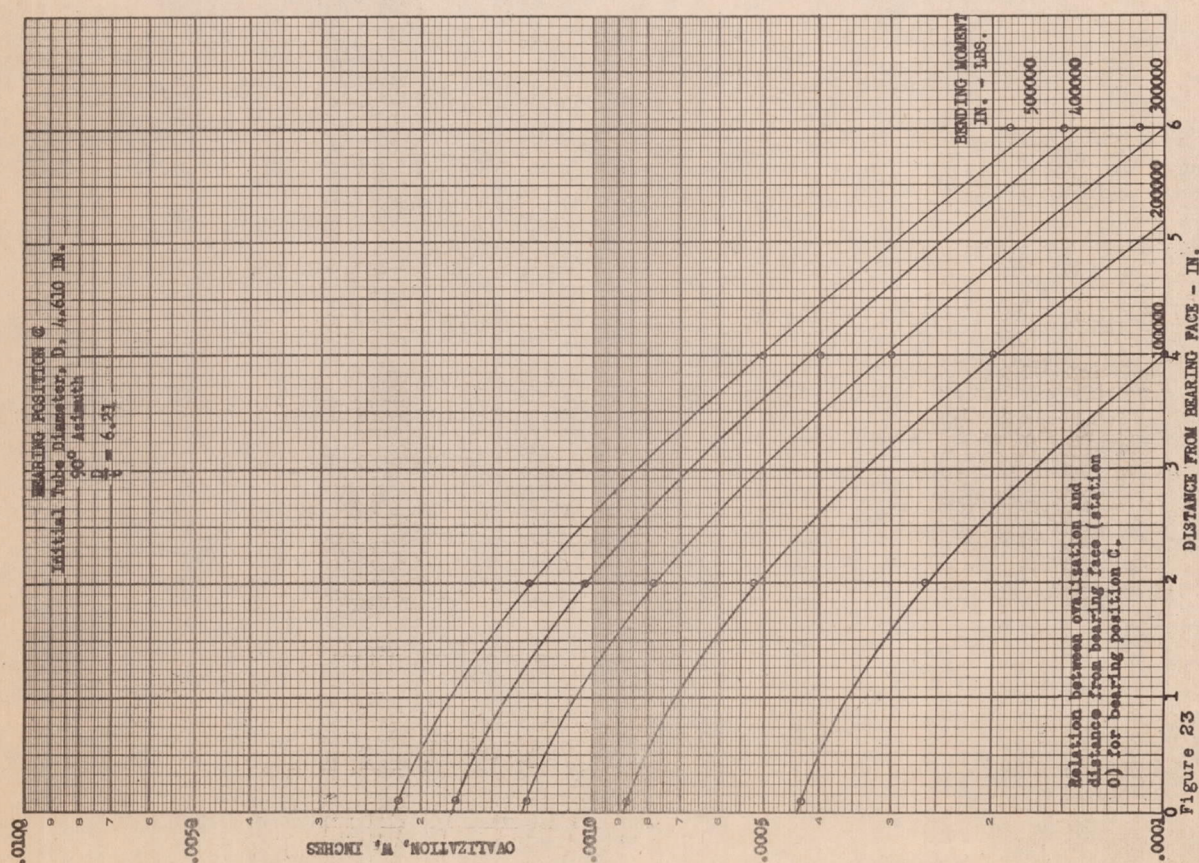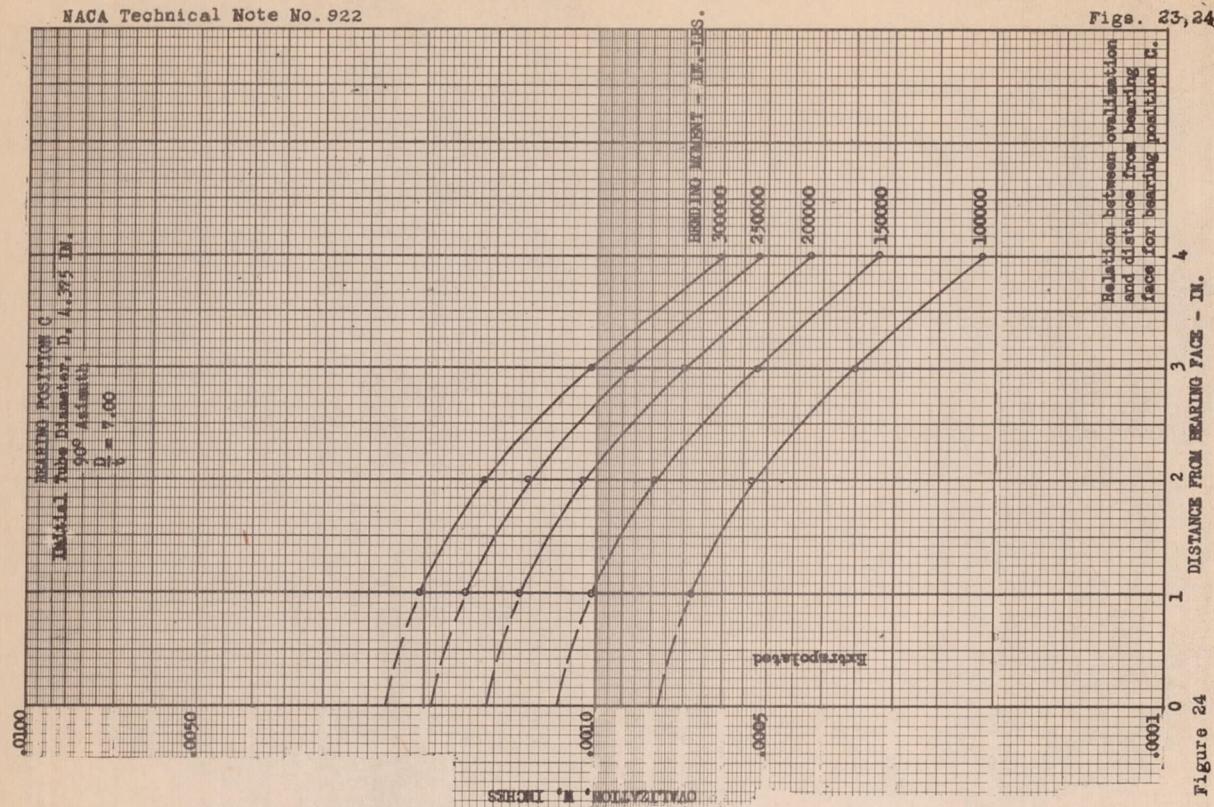Initial Tube Diameter, D, 3.650 IN.
90° Azimuth
$\frac{D}{t}$ = 13.9

BENDING MOMENT - IN. LBS.

240000

200000

150000

100000

60000

OVALIZATION, W, INCHES

Extrapolated

DISTANCE FROM BEARING FACE - IN.

Figure 29

Variation of ovalization
with distance from bear-
ing face.

BEARING POSITION D
Initial Tube Diameter, D, 3.650 IN.
90° Azimuth
$\frac{D}{t}$ = 13.9

BENDING MOMENT - IN. LBS.

200,000

160,000

120,000

80,000

40,000

OVALIZATION, W, INCHES

Extrapolated

DISTANCE FROM BEARING FACE, INCHES

Figure 30

Variation of ovalization with distance
from bearing face (Station zero).

BEARING POSITION E
Initial Tube Diameter, D, 3.650 IN.
90° Azimuth
$\frac{D}{t} = 13.9$

BENDING MOMENT — IN. LBS.

200000

160000

120000

80000

40000

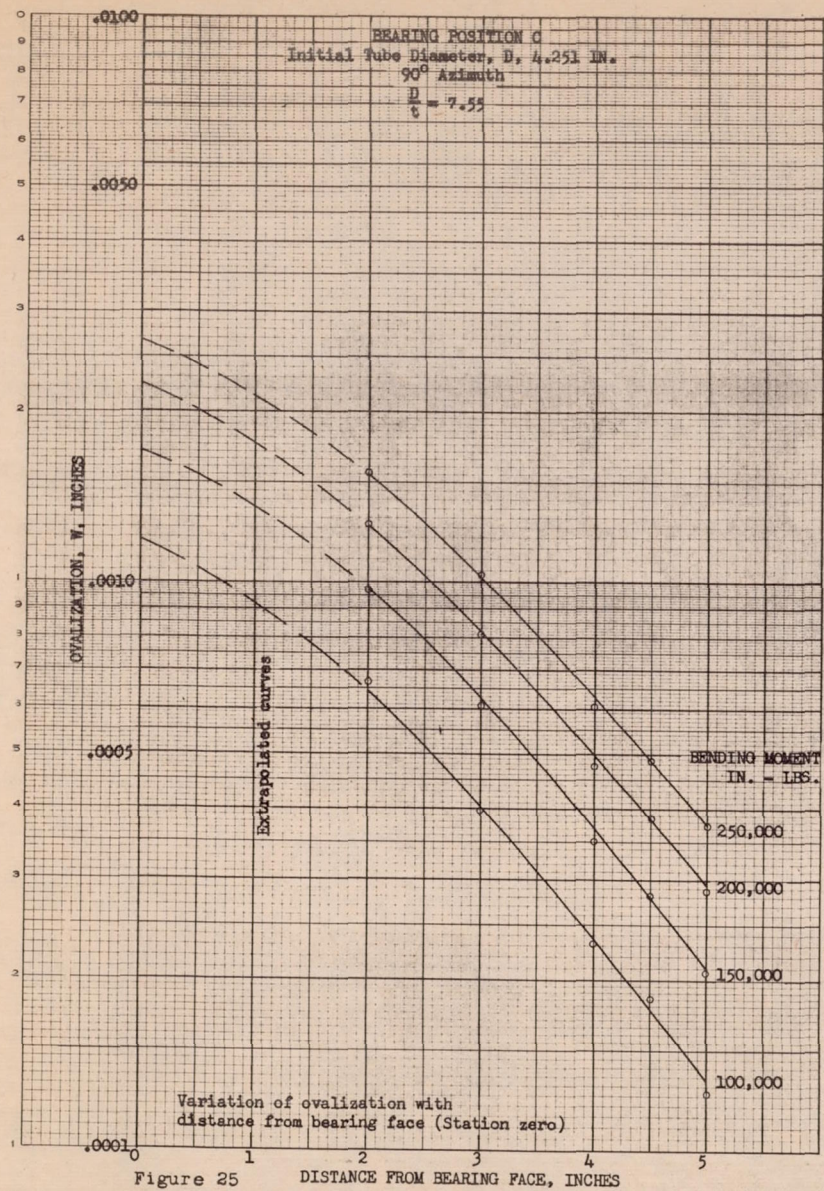OVALIZATION, W, INCHES

Extrapolated

Variation of ovalization
with distance from bearing face.

Figure 31   DISTANCE FROM BEARING FACE — IN.

BEARING POSITION F
Initial Tube Diameter, D, 3.650 IN.
90° Azimuth
$\frac{D}{t} = 13.9$

BENDING MOMENT
IN. — LBS.

140000

120000

100000

60000

20000

OVALIZATION, W, INCHES
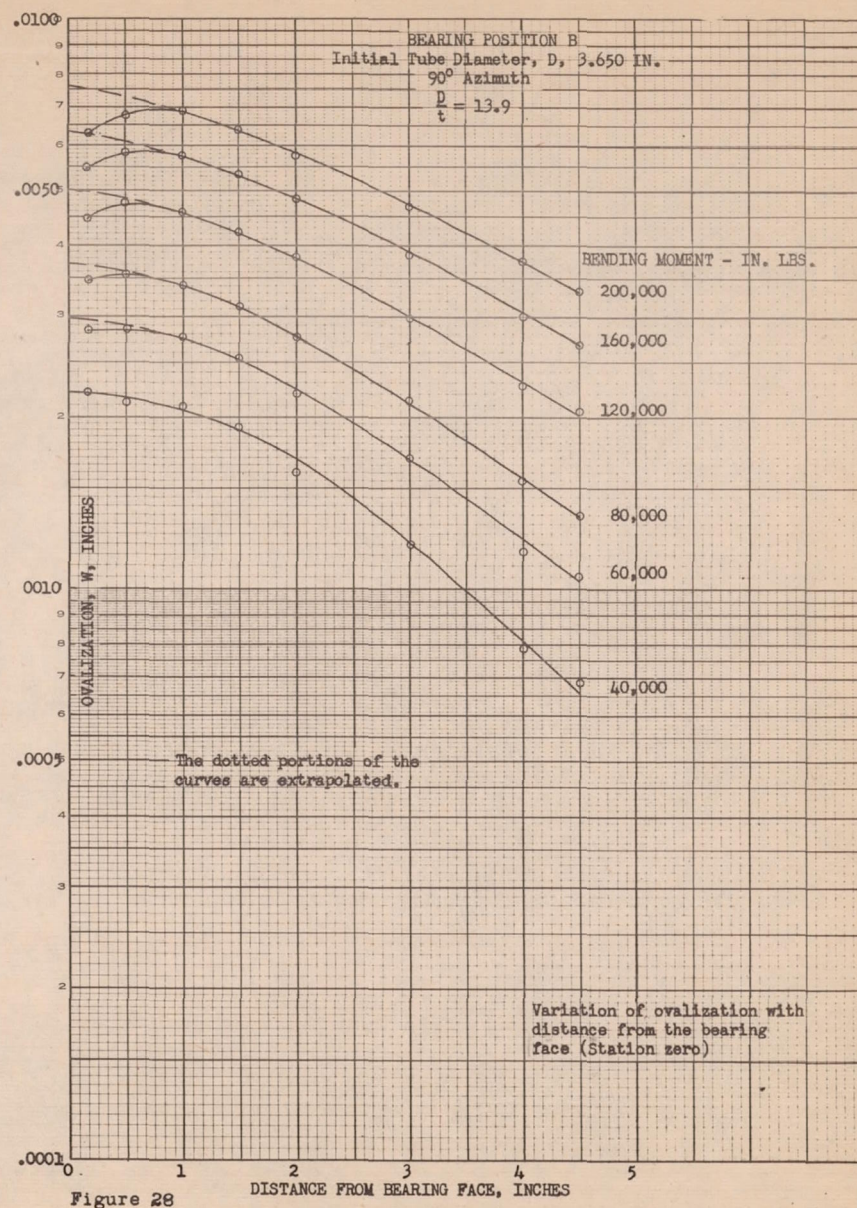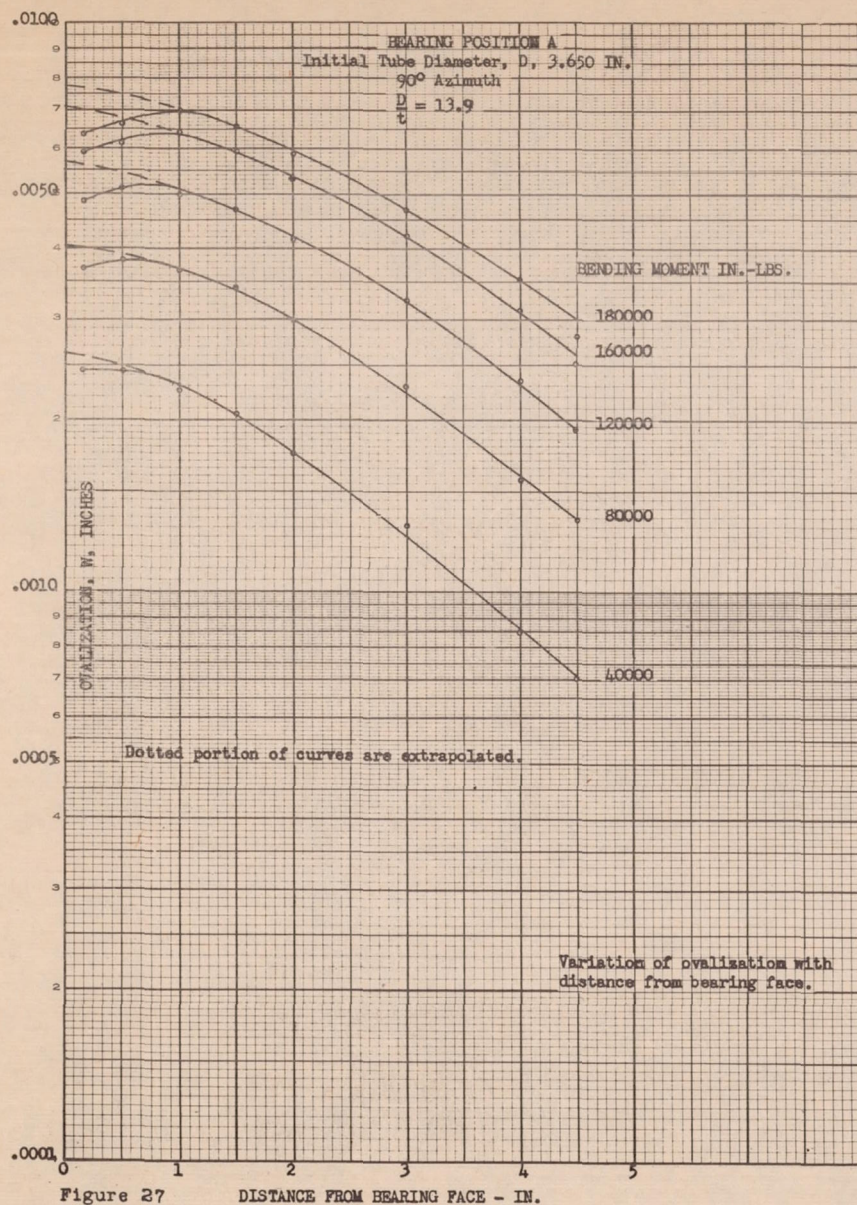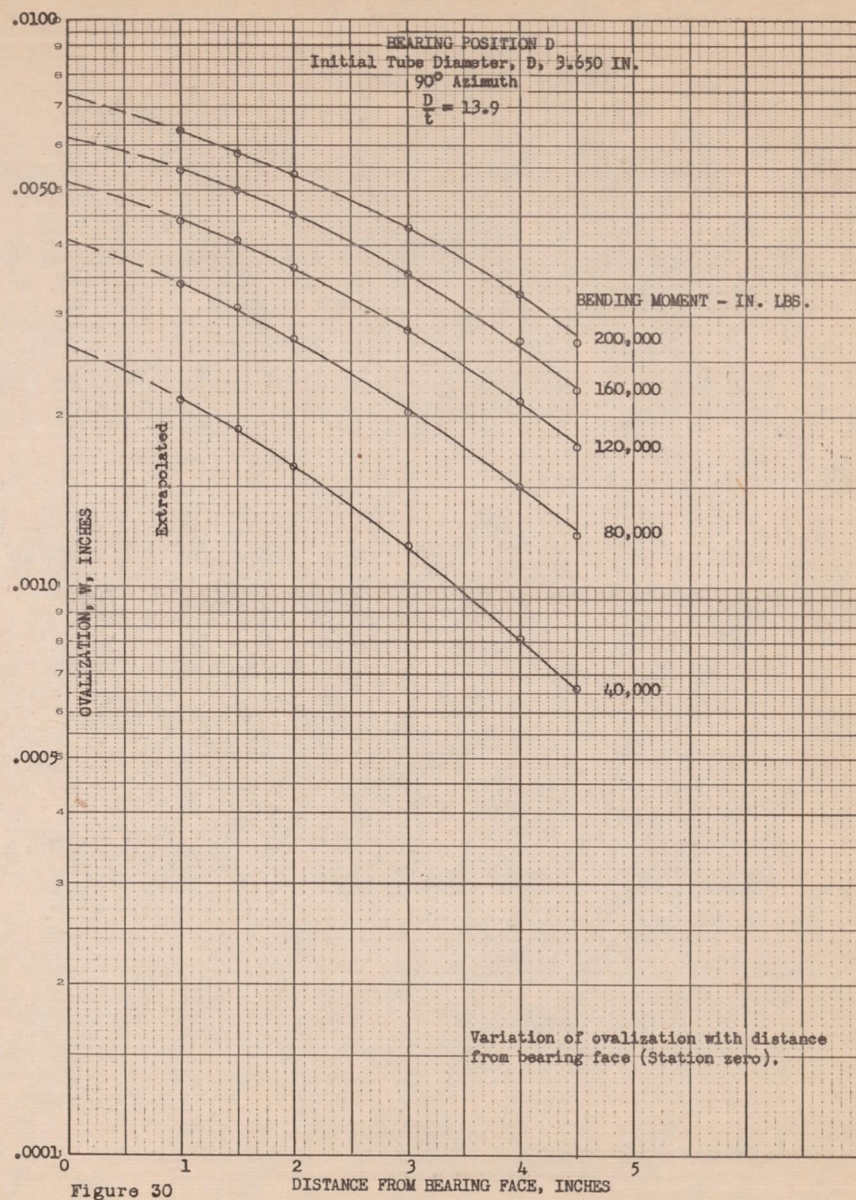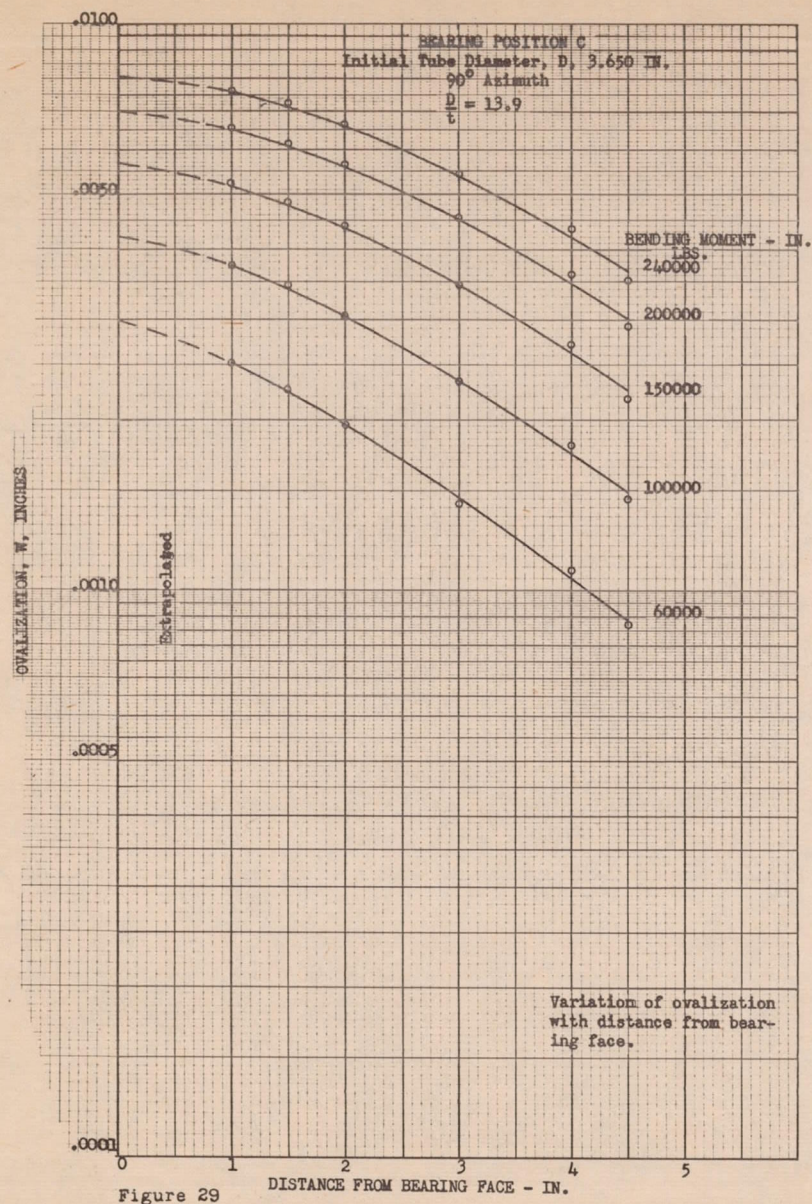
Extrapolated

Variation of ovalization
and distance from bearing
face.

Figure 32   DISTANCE FROM BEARING FACE — IN.

BEARING POSITIONS B, C, D, and E
Initial Tube Diameter, D, 4.610 IN.
90° Azimuth
$\frac{D}{t}$ = 6.21

CURVE

BEARING POSITION B

BEARING POSITIONS C, D, and E

OVALIZATION, W, INCHES

Variation of ovalization and
bending moment at different
bearing position, all points
being taken at station zero.

Figure 33   BENDING MOMENT - IN. LBS. x 10⁴

BEARING POSITIONS A, B, C, D, and E
Initial Tube Diameter, W, 4.375 IN.
90° Azimuth
$\frac{D}{t}$ = 7.00

OVALIZATION, W, INCHES

BEARING POSITION A

BEARING POSITION B

BEARING POSITION C
BEARING POSITION D

Variation of ovalization with
bending moment at different
bearing positions. Curves are
plotted from extrapolated data
at station zero.

Figure 34   BENDING MOMENT - IN. LBS. x 10⁴

Figure 36

BEARING POSITIONS A, B, C, D, and E
Initial Tube Diameter, D, 3.929 IN.
90° Azimuth
$\frac{D}{t} = 9.77$

BEARING POSITION A
BEARING POSITION B
BEARING POSITION C
BEARING POSITION D
BEARING POSITION E

Variation of ovalization with bending moment for different bearing position. Data were obtained by extrapolating semi-log curve to station zero.

BENDING MOMENT – IN. LBS. x 10^4

OVALIZATION, W, INCHES

Figure 35

BEARING POSITIONS A, B, C, D, and E
Initial Tube Diameter, D, 4.251 IN.
90° Azimuth
$\frac{D}{t} = 7.55$

BEARING POSITION A

BEARING POSITION B
BEARING POSITION D
BEARING POSITION C
BEARING POSITION E

Variation of ovalization and bending moment for different bearing positions. Curves are plotted from extrapolated data at station zero.

BENDING MOMENT – IN. LBS. x 10^4

OVALIZATION, W, INCHES

BEARING POSITION A, B, C, D, and E
Initial Tube Diameter, D, 3.650 IN.
90° Azimuth
$\frac{D}{t} = 13.9$

BEARING POSITION A →   ← BEARING POSITION E
                        BEARING POSITION B
                        BEARING POSITION D
                        BEARING POSITION C

OVALIZATION, W, INCHES

Variation of ovalization with bending moment
for different bearing positions. The data
for these curves were obtained by extrapolation.

BENDING MOMENT, IN. LBS. x 10⁴

Figure 37

Figure 38

Variation of log (-log a)

with $\dfrac{J}{D/t}$

Bearing Position

A   B   C   D   E

D/t

6.21

7.00

7.55

9.77

13.9

Log (-log a)

J/D/t   IN.

Figure 39

Variation of "s"
with
Cantilever Length, L_c in inches

Log (Log b)

Log (Log L)

Variation of s with

Cantilever Length, L, in inches

Figure 40   Cantilever Length, L, in inches

Variation of b with D/t

Figure 41   D/t   inches